FUEL CELL PROTECTION

The present invention relates to a method of protecting a fuel cell and to a fuel cell booster circuit for implementing the method of protection.

Figure 1 shows an example of a conventional architecture of a power generator 10 comprising a fuel cell 12. The fuel cell 12 receives a stream of feed air driven by a compressor 14 at a feed rate Q_i and discharges a stream of exhaust air at a discharge rate Q_o. The fuel cell 12 consists of a set of individual cell elements (not shown) arranged in series and can be represented, schematically, by a voltage generator for generating a voltage between two terminals 16, 17. A chemical electrolysis reaction consuming oxygen delivered by the stream of feed air takes place in each individual cell element. The voltage across the terminals 16, 17 of the fuel cell 12, or the cell voltage, is noted by U_c and the current delivered by the fuel cell 12, or the cell current, is denoted by I_c. The terminal 17 is connected to a reference potential GND, for example ground, and the terminal 16 is connected to an input node E of a power converter 18. The converter 18 delivers power P_o demanded by a user, called hereafter the user power.

The power generator 10 includes a booster circuit 19 comprising a battery 20 and a diode 22 that are connected in series. One terminal of the battery 20 is connected to the anode of the diode 22 and the other terminal is connected to ground GND. The cathode of the diode 22 is connected to the node E. The booster circuit 19 delivers a current I_b or booster current in order to assist the fuel cell 12. The battery 20 is recharged by a battery charger (not shown).

The total current I_t received by the power converter 18 corresponds to the sum of the cell current I_c and of the booster current I_b. In normal operation, all of the current I_t is delivered by the cell, and the booster current I_b is zero. During rapid large transients in the user power P_o, the fuel cell 12 does not necessarily have the capacity to immediately deliver all of the current I_t demanded. The cell voltage U_c consequently tends to drop suddenly. The diode D is then turned on and the booster circuit 19 temporarily delivers a booster current I_b in order to meet the user power demand until the fuel cell is capable of delivering all of the demanded current I_t.

Figures 2A to 2E show in greater detail for example the time variation of characteristic signals of the power generator 10 of figure 1 during a transient in the user power P_o. Curves 25 to 29 show the total current I_t, the cell current I_c, the cell voltage U_c, the feed air rate Q_i and the oxygen content xO_2 of the stream of exhaust air, respectively. The power P_o is equal, in succession, to idle power (for example 200 watts) for 0.1 seconds, to twice the nominal power of the fuel cell 12 (for example 4 kilowatts) for one second and, finally, to the nominal power of the fuel cell 12.

When the user power P_o is equal to the idle power, the oxygen content xO_2 is substantially equal to 12%. This corresponds to a steady-state situation for which the stoichiometric oxygen consumption factor of the overall chemical reaction that takes place within the fuel cell 12 is around 2. The air feed rate Q_i then stabilizes, so as to ensure such a stoichiometric factor. The total current I_t is entirely delivered by the fuel cell 12 and the cell voltage U_c is high.

When the user power P_o increases to twice the nominal power, the total current I_t suddenly increases and the

cell voltage U_c suddenly drops, before stabilizing to about 50 volts.

The compressor 14 receives a specified setpoint for the air feed rate Q_i on the basis of the total current I_t. However, the inertia of the compressor 14 results in a delay between the moment when the compressor receives a specified setpoint and the moment when the compressor 14 delivers the feed air at the rate Q_i corresponding to the specified setpoint. A few seconds are therefore needed for the air feed rate Q_i to increase.

Just after the user power P_o has increased to twice the nominal power, the fuel cell 12 again has enough air to deliver all of the total current I_t for a short period (for about 0.1 s). However, since the speed of the compressor 14 has not yet increased, the fuel cell 12 receives air at a rate Q_i that is substantially identical to the rate of air received when the user power P_o was equal to the idle power. The fuel cell 12 therefore consumes all the oxygen available to it in its internal volume. This may be confirmed by the curve shown in figure 2E by the drop in oxygen content xO_2 in the stream of exhaust air. When the xO_2 content reaches about 4%, some of the cell elements of the fuel cell 12 that are less well supplied, especially because of very small geometrical differences at manufacture, see their voltage drop just below zero. The polarity of such cells is therefore reversed. This causes an additional drop in the cell voltage U_c, so that the diode 22 is turned on and allows the battery 20 to deliver part of the total current I_t. The current delivered by the cell I_c then drops and stabilizes at a value twice the value corresponding to the idle power. This corresponds to a stoichiometric oxygen consumption factor of the overall chemical reaction within the fuel cell 12 equal to 1. Practically all the oxygen introduced into the fuel cell 12 is therefore consumed.

Next, as the speed of the compressor 14 increases so the air feed rate Q_i and the cell current I_c increase. Throughout this phase, the stoichiometric oxygen consumption factor remains equal to 1 and the oxygen content xO_2 remains less than 4%. An increasingly high current therefore flows through the cell elements of the fuel cell 12 that have their polarity reversed. There is therefore a risk of such cell elements being damaged, thus reducing their lifetime.

The aim of the present invention is to provide a method for protecting a fuel cell and to provide a fuel cell booster circuit for implementing the method of protection, preventing the phenomenon of polarity reversal of cell elements of the fuel cell during user power transients.

The object of the present invention is also to provide a fuel cell booster circuit for implementing the method of protection which is of simple design and requires little modification of the architecture of the power generator.

To achieve these objects, the present invention provides a method of protecting a fuel cell, consisting of individual cell elements, delivering electric power in response to a power demand, a booster circuit being suitable for delivering additional electric power in order to assist the fuel cell, consisting in the following: a parameter representative of the minimum voltage is determined from among the voltages across the terminals of each individual cell element; and the additional electric power delivered by the booster circuit is controlled so that said minimum voltage remains above a specified threshold.

According to one way of implementing the invention, the booster circuit maintains the voltage across the terminals of the fuel cell on the basis of a setpoint determined from said parameter.

According to one way of implementing the invention, the individual cell elements of the fuel cell are supplied with oxygen by a stream of feed air, the fuel cell discharging a stream of exhaust air, said parameter being the image of the oxygen content of the stream of exhaust air, and the booster circuit delivering additional electric power so that the oxygen content is above a specified threshold.

According to one way of implementing the invention, said parameter is the image of the derivative of the voltage across the terminals of the fuel cell, the booster circuit delivering additional electric power in order for the derivative of the voltage across the terminals of the fuel cell to be above a specified threshold.

According to one way of implementing the invention, the control of the additional electric power delivered by the booster circuit consists in determining an image current that is the image of the current delivered by the fuel cell; in filtering the image current by a low-pass filter; in delivering a comparison signal equal to the sum of a constant and of the filtered image current multiplied by a correction coefficient; and in controlling the additional electric power delivered by the booster circuit so that the image current of the current delivered by the fuel cell converges on the comparison signal.

The present invention also provides a booster device for a fuel cell, consisting of a set of individual cell elements and suitable for delivering electric power in

response to a power demand, said device being suitable for delivering additional electric power in order to assist the fuel cell, which device comprises a circuit for determining a parameter representative of the minimum voltage from among the voltages across the terminals of each individual cell element; and a circuit for controlling the additional electric power delivered so that said minimum voltage remains strictly positive.

According to one embodiment of the invention, the device further includes a voltage source; a circuit for delivering a setpoint; and a chopper circuit connected to the voltage source, which receives said setpoint and fixes the voltage across the terminals of the fuel cell on the basis of said setpoint.

According to one embodiment of the invention, the circuit for delivering the setpoint comprises: a circuit for determining an image current that is the image of the current delivered by the fuel cell; a circuit for determining a comparison signal equal to the sum of a constant and of the image current multiplied by a correction coefficient; a comparison circuit that delivers an error signal corresponding to the difference between the image current and the comparison signal; and a regulator that delivers the setpoint in order to minimize the error signal.

According to one embodiment of the invention, the regulator is of the integral or proportional-integral type.

These objects, features and advantages, and also others of the present invention will be explained in detail in the following description of particular embodiments, given by way of nonlimiting example and in conjunction with the appended figures in which:

- figure 1, described above, shows a conventional architecture of a fuel cell power generator;
- figures 2A to 2E, described above, show the variation in characteristic parameters of the power generator of figure 1 during a power transient;
- figure 3 shows, schematically, a fuel cell power generator comprising an exemplary embodiment of a booster circuit according to the invention;
- figure 4 shows an example of a control signal used by the booster circuit of figure 3;
- figure 5 shows schematically a first embodiment of a control circuit for the booster circuit of figure 3;
- figure 6 shows a second embodiment of the control circuit;
- figures 7A to 7H show the variation in characteristic parameters of the power generator of figure 3 during a power transient;
- figure 8 shows schematically a third embodiment of the control circuit; and
- figure 9 shows a more detailed exemplary embodiment of the control circuit of figure 8.

In the various figures, identical elements are denoted by identical references.

The method of protection according to the present invention consists in providing a booster circuit suitable for assisting the fuel cell 12 before certain individual cell elements of the fuel cell 12 undergo polarity reversal.

Figure 3 shows a power generator 10 similar to the generator shown in figure 1, equipped with a booster circuit 30 according to the invention. The booster circuit 30 comprises an inductor 32 connected in series with the battery 20, between the battery 20 and the diode 22, a capacitor 34, one terminal of which is

connected to the cathode of the diode 22 and the other terminal of which is connected to ground GND, and a controlled switch 36, one terminal of which is connected to the anode of the diode 22 and the other terminal of which is connected to ground GND. The switch 36, consisting for example of an MOS transistor, is controlled by a control signal S_{con} delivered by an oscillator circuit 38 (OSC) on the basis of a setpoint S_o delivered by a control circuit 40 (CON). The circuit consisting of the controlled switch 36, the inductor 32 and the capacitor 34 corresponds to a chopper circuit. The booster circuit 30 therefore imposes a cell voltage U_c that depends on the setpoint S_o. The voltage across the terminals of the battery 20 and the current delivered by the battery 20 are denoted by U_{bat} and I_{bat}, respectively.

Figure 4 shows an example of the time variation of the control signal S_{con}. This is a rectangular wave signal, of periodic duty cycle α and period T, varying for example between the zero value ("0") and a high value ("1"). The setpoint S_o delivered by the control circuit 40 is the image of the duty cycle α. The oscillating circuit 38 is designed in a conventional manner and will not be described further below. When the duty cycle α is equal to zero, the booster circuit 30 shown in figure 3 is approximately equivalent to the booster circuit 19 shown in figure 1, given the small amount of energy stored in the inductor 32 and the capacitor 34 relative to the energy present in the battery 20 and that present in the fuel cell 12.

Figure 5 shows schematically a first embodiment of the control circuit 40. The control circuit 40 receives a current Im_t that is the image of the total current I_t, and a current Im_p that is the image of the cell current I_p. A first low-pass filter 42 (F1) receives the current Im_t and delivers a filtered current Im_t*. A second low-

pass filter 44 (F2) receives the current Im_p and delivers a filtered current Imc*. The filters 42, 44 eliminate the excessively sudden variations in the currents Im_t and Im_p. A subtractor 46 delivers a current Im_b equal to the difference between the currents Im_t* and Imc*. The current Im_b therefore corresponds to the image of the current delivered by the booster circuit 30. A second subtractor 48 determines an error signal ε equal to the difference between the current Im_b and a reference current I_{ref}. A regulator 50 (PI) of the proportional-integral type receives the error signal ε and delivers the setpoint S_o.

By choosing a time constant of the filter 42 such that the delay induced by the filter 42 corresponds to the delay of the compressor 14, the current Im_t* is representative of the drive speed of the compressor 14. The current Imc* is representative of the influence of the cell current on the amount of oxygen in the fuel cell 12. The current Im_b is then representative of the amount of oxygen present in the fuel cell 12, that is to say representative of the oxygen content xO_2 in the stream of exhaust air. The method of correction according to the first way of implementing the invention consists in ensuring that the oxygen content xO_2 is always above a reference amount, for example 10%. This ensures that in no case does the voltage across the terminals of one of the individual cell elements of the fuel cell 12 drop below zero volts.

The regulation of the control circuit 40 is also designed in such a way that the cell current I_c does not increase too suddenly and therefore limits the rising slope of the cell current I_c. In addition, the regulation must be sufficiently insensitive to prevent a booster current I_b being delivered when the variation in the total current I_t is sufficiently rapid and small. Such variations correspond for example to low-frequency

oscillations, which may arise when the voltage delivered to the customer is a single-phase AC voltage, or to interference, for example electromagnetic interference, in the current sensors. Furthermore, intrinsic protection of the operation of the booster circuit 40 must prevent a booster current I_b being delivered if the cell voltage U_c exceeds a specified threshold. Finally, a negative booster current I_b must not be delivered to the input of the fuel cell 12.

Figure 6 shows a second exemplary embodiment of the control circuit 40 according to the invention. The setpoint S_o is determined in such a way that the image current Im_c, the image of the cell current I_c, never exceeds a state value βImc^*+I_0. The filtered current Imc^* is obtained from Im_c by a first-order or a second-order low-pass filter with a time constant of the order of a few tenths of a second. The current I_0 corresponds to a constant value and is the image of the current delivered by the fuel cell 12 when the compressor 14 is idling. The coefficient β is a constant greater than 1, for example around 1.2. Regulation is obtained by a regulator of the proportional-integral type.

The control circuit 40 receives the current Im_c at an input terminal IN. A resistor R_0 connects the mid-point between the input terminal IN and a node J to ground GND. The node J constitutes the input point of a first low-pass filter consisting of a resistor R_1 placed between the node E and a node K and a capacitor C_1 placed between the node K and ground GND. The node J constitutes the input point of a second low-pass filter consisting of a resistor R_2 placed between the node J and a node L, and of a capacitor C_2 placed between the node G and ground GND. The node K is connected to the inverting input (-) of an operational amplifier 52 via a resistor R_3. The node L is connected to the noninverting input (+) of the operational amplifier 52

via a resistor R_4. A resistor R_5 is placed between the inverting input of the operational amplifier 52 and ground GND. The operational amplifier 52 delivers the setpoint S_o. The inverting input of the operational amplifier 52 is connected to the output of the operational amplifier 52 via a capacitor C_3 connected in series with a resistor R_6. The circuit formed by the resistors R_4, R_5, R_6 and the capacitor C_3 constitutes a regulator of the proportional-integral type. The control circuit 40 includes a protection circuit 54 comprising a diode D_1, a resistor R_7 and a diode D_2, these components being connected in series between the node J and the noninverting input. The anode of the diode D_1 is connected to the node J and the anode of the diode D_2 is connected to the noninverting input. A resistor R_8 connects the cathode of the diode D_2 to ground GND.

The first low-pass filter has a pass band of a few tens of hertz in order to give the control circuit 40 greater robustness. Furthermore, such a filter is not a problem as long as the reaction time of the regulation of the voltage U_c is shorter than the time that causes the reserve of oxygen in the fuel cell 12 to decrease (which is generally equal to a few tens of milliseconds).

To give an example, for a cell current I_c varying between 0 and 100 amps, the current Im_c may vary substantially between 4 and 20 milliamps. The non zero value of the current Im_c associated with the zero value of the cell current I_c allows the constant I_0 of the regulation to be obtained. The coefficient β is set by the resistor R_4. As an example, the operational amplifier delivers a setpoint S_o that varies between 0 and 5 volts, for the delivery of a cell voltage U_c that varies between 45 and 90 volts. For example, to obtain such a regulation, the resistors R_0, R_1, R_2, R_3, R_4, R_5,

R_6, R_7 and R_8 are equal to 250 ohms, 4.7 kilohms, 4.7 kilohms, 22 kilohms, 100 kilohms, 47 kilohms, 100 kilohms, 1 kilohm and 10 kilohms, respectively. The capacitors C_1, C_2 and C_3 have capacitances of 100 microfarads, 2.2 microfarads and 22 nanofarads, respectively. The operational amplifier 52 is of the LM6142 type. The diodes D_1, D_2 are for example of the 1N4148 type.

When the cell voltage that would be obtained with a given control signal S_{con} is below the actual voltage U_c of the cell, the booster circuit 30 cannot actually deliver the voltage corresponding to the control signal S_{con}. Such a case corresponds to the steady state for which the value of the duty cycle has to be strictly equal to zero.

When the booster circuit 30 assists the fuel cell 12, the cell voltage U_c obtained by the regulation must preferably not increase too slowly. The minimum level of the cell voltage U_c obtained by the regulation is therefore maintained at a value slightly below the average cell voltage. The cell voltage U_c obtained by the regulation is therefore designed to saturate at a minimum value well above zero, for example 45 volts.

The protection circuit 54 speeds up the reduction in the setpoint S_o when the current Im_c suddenly decreases, in order to prevent current being reinjected into the fuel cell 12.

Figures 7A to 7H show curves 60 to 67 representative of the time variation of the total current I_t, of the cell current I_c, of the cell voltage U_c, of the air feed rate Q_i, of the oxygen content xO_2 in the stream of exhaust air, of the current I_b of the booster circuit, of the battery voltage U_{bat} and of the battery current I_{bat}, respectively, for the same power transient as in

figures 2A to 2E with the control circuit 30 shown in figure 6.

At the moment when the user power goes from an idle level to twice the nominal power, the fuel cell 12 starts to deliver, for a very short time, almost all of the total current I_t demanded, consuming the oxygen that it contains. The booster circuit 30 then delivers almost immediately almost all of the total current I_t. The cell current I_c therefore suddenly drops and then slowly increases as the speed of the compressor 14 increases. The method of protection according to the invention is therefore well able to limit the drop in the oxygen content xO_2, and therefore in the voltages across the terminals of the individual cell elements of the fuel cell 12. Thus, any deterioration of the cell elements of the fuel cell 12 is avoided.

Figure 8 illustrates schematically a third embodiment of the control circuit 40 in which the regulation ensures that the derivative of the cell voltage U_c is always above a specified threshold U'_{ref}. This thus prevents a sudden drop in the cell voltage U_c, which is a good indicator signaling the risk that the voltages across the terminals of certain individual cell elements of the fuel cell 12 have fallen below zero. The risk of cell elements of the fuel cell 12 deteriorating is thus reduced.

The input terminal IN of the control circuit 40 receives an image voltage Um_c that is the image of the cell voltage U_c. The voltage Um_c is delivered by a low-pass filter 68 (F), for example a first-order filter. A derivator 70 (d/dt) receives the output from the low-pass filter 68 and delivers a signal Um'_c that is the image of a derivative of the cell voltage U_c. A subtractor 72 delivers an error signal ε^* equal to the difference between the signal Um'_c and the reference

threshold U'_{ref} to a regulator 74, for example of the proportional-integral type, which delivers the setpoint S_o.

Figure 9 shows a more detailed exemplary embodiment of the control circuit 40 of figure 8. The input terminal IN that receives the voltage U_c corresponds to the input of a low-pass filter consisting of a resistor R_9 connected between the input terminal IN and a node M, and a capacitor C_4 connected between the node M and ground GND. A derivator is formed by a capacitor C_5 connected between the node M and the inverting input (-) of an operational amplifier 76. A resistor R_{10} is connected between the inverting input and a defined potential U_d. The noninverting input (+) of the operational amplifier 76 is connected to ground GND. In the present embodiment, the regulator is of the pure integral type and comprises a capacitor C_6 connected between the inverting input and the output of the operational amplifier 76. The operational amplifier 76 delivers the setpoint S_o. Two diodes D_3, D_4 in series are connected in parallel with the capacitor C_6. The anode of the diode D_3 is connected to the inverting input of the operational amplifier 76 and the cathode of the diode D_4 is connected to the output of the operational amplifier 76.

The resistor R_7 regulates the threshold U'_{ref}. The diodes D_3, D_4 impose a value slightly below zero (here, about -1.2 volts) for saturating the integral of the regulator. This integral will rapidly exceed the zero value at the moment of a transient for greater rapidity (otherwise this integral saturates the negative supply voltage of the operational amplifier 76, well below 0 volts.

The present invention provides a method of protecting a fuel cell of a power generator that allows the power

delivered by the fuel cell to be regulated so as to prevent the individual cell elements making up the fuel cell from deteriorating.

Of course, the present invention is capable of various alternative embodiments and modifications that will become apparent to those skilled in the art. In particular, the battery of the booster circuit may be replaced with an accumulator, a bank of capacitors, a super capacitor, etc.